METHOD AND APPARATUS FOR CHANNEL EQUALIZATION AND CYCLOSTATIONARY INTERFERENCE REJECTION FOR ADSL-DMT MODEMS

5

FIELD OF THE INVENTION

The present invention relates generally to ADSL-DMT modulation and in particular a method and apparatus for reducing or canceling crosstalk disturbances to ADSL-DMT modems within environments exhibiting ISDN interference.

10

BACKGROUND OF THE INVENTION

With the advent of the Internet and other high-bandwidth electronic communication systems and the consumer demand for information, interactive gaming and electronic entertainment such as video on-demand, there has been a substantial need

15 for reliable and affordable high bandwidth mediums for facilitating data transmissions between service providers and their customers. In relation to the requirement that such mediums be affordable to consumers and structurally attainable in a cost-effective manner for providing service to customers involves using already existing copper wire telephone systems (plain old telephone system or POTS) infrastructure.

20 Relating specifically to the adaptation of POTS telephone lines to carry data at a higher bandwidth is the adaptation of a digital connection known as ISDN (Integrated Services digital Network) in which a date rate of 64 Kilobits per second is supported.

Most recently, ISDN services has largely been replaced in certain parts of the world by broadband internet services, such as Digital Subscriber Line (xDSL). Standards and protocols for many flavors of DSL have been proposed such as VDSL (for high speed digital transmission over short distances), HDSL, SDSL (with symmetric transmission

5   speeds) and ADSL (with asymmetric uplink and downlink transmission speeds). Relating specifically to ADSL, ADSL essentially operates by formatting signals using various Time Domain Equalization techniques to send packets over copper wire at high data rates. ADSL is considered advantageous for its ability to provide very high data rates in the downstream (i.e., from service provider to the user) direction by sacrificing

10   speed in the upstream direction. Consequently, end user costs are minimized by providing higher speeds in the most commonly used direction.

Two of the proposed standards for the specific requirements for an ADSL system operation are set forth by the International Telecommunications Union, Telecommunications Standardization Section (ITU-T). A first, conventional, ADSL

15   standard is described in ITU-T Recommendation G.992.1 - "Asymmetric Digital Subscriber Line (ADSL) Transceivers", also known as full rate ADSL (G.dmt) which describes three types of system operation modes, Annex A, Annex B and Annex C. Annex A describes the specific requirements for an ADSL system operating in the frequency band above the conventional frequency band employed in the POTS system.

20   Annex B describes the specific requirements for an ADSL system operating in the frequency band above the conventional frequency band employed by ISDN lines as

defined in ITU-T recommendation G.961 appendices I and II. Lastly, Annex C describes

the specific requirements for an ADSL system operating in the same cable as ISDN as

defined in ITU-T recommendation G.961 appendix III. Annex A and B are primarily

used in North America and Europe, whereas Annex C (ADSL above POTS) co-existing

5   with TCM-ISDN (Time Compression Multiplexed (TCM) ISDN - a type of "ping-pong"

time division transmission) is implemented primarily in Japan. For purposes of clarity,

the body of G.992.1 is fully incorporated herein by reference.

A second, more recently proposed ADSL standard is the G.992.2 or 'G.lite'

standard, further described in ITU-T Recommendation G.992.2 - "Splitterless

10   Asymmetric Digital Subscriber Line (ADSL) Transceivers", which comprise Annex A

(FDM ADSL above POTS) mostly implemented in North America, Annex B (ADSL

above ISDN) mostly implemented in Europe and Annex C (ADSL above POTS, co-

existing with TCM-ISDN) implemented mostly in Japan which is also bodily

incorporated by reference herein. The G.lite standard is a variant of the G.992.1

15   standard, with modifications directed primarily to work in a splitterless environment (i.e.,

without a splitter at the remote user end to separate the voice traffic from the digital data

traffic). ADSL is made available in two modulation schemes known as Discrete

Multitone (DMT) and Carrierless Amplitude and Phase (CAP). An asymmetric model

such as ADSL complements the residential profile of Internet use: Masses of multi-media

20   and text is transferred downstream, and undemanding levels of traffic make their way

upstream.

The present application is directed primarily to the DMT mode of modulation, wherein DMT slices available frequencies into 256 channels of 4.3125KHz each, within a bandwidth range of 30 KHz to 1104 KHz. Unfortunately, with such a system ISDN signals either co-transmitted in the same wire or provided in close proximity to the ADSL

5   DMT signals can create a significant source of interference. ISDN uses a baseband modulation of different baud rates, such as, for example, 80 KHz for Annex B and 320 KHz for Annex C. However, from the bandwidth allocated for ISDN and ADSL, there is an overlap of bandwidth between the two, and that results in a strong crosstalk from having ADSL and ISDN signal transmission on the same cable bundle as it is found in

10   Japan where Annex C and lesser degree of crosstalk in Europe where Annex B is implemented.

As defined in Annex B of the G.dmt ITU-T recommendation, a new ADSL service might be required to operate over ISDN on the same twisted pair. The partial spectrum overlapping of ISDN into the ADSL bandwidth limits the operation of the

15   ADSL system, as the useful ISDN signal clearly supersedes in this configuration any other noise source. However, in both situations described above, the interference signal presents some statistical properties that can be used to successfully mitigate or eliminate completely the effects of the interference onto the ADSL transmission. These properties originate from the cyclostationary nature of the interference: i.e. interferers and cross-talk

20   statistics are periodic with period equal to some time interval related to the baud rate of the modulated interference signal. A dual definition of cyclostationarity is that frequency-

shifted versions of the baud modulated interferer can be highly correlated with the

original signal. More formally, a cyclostationary signal is defined as a signal having

periodically time-varying second order statistics (i.e. periodic autocorrelation), for

example, if a signal x is cyclostationary with a cyclic frequency α, then there is non-

5   zero correlation between the signal x and the same signal x, shifted in frequency by α.

Referring now to Figure 1, there is shown a graphical representation of a spectrum

of a typical ISDN interferer as depicted in ADSL, Annex B. The property of

cyclostationarity of the signal can be interpreted from Figure 1, where each side-lobe of

the modulated signal is a filtered replica of the main (base-band) lobe i.e., a strong

10   correlation exists between each side-lobe of the transmitted spectrum. A shaping filter at

the transmitter preserves significant energy in the secondary lobes, making it possible to

detect strong correlation between adjacent frequency bands in the signal received on the

line. Baud-modulated signals such as ISDN, HDSL, SDSL (to name a few) which are

used in data communication exhibits cyclostationary property by design, but unlike

15   ISDN, the others do not exhibit a property of a strong correlation of each side lobes of the

transmitted spectrum. This property is inherent to the transmission of a flow of

statistically independent data symbols, chosen among a given symbol set, each symbol is

characterized by a given phase and amplitude and is stationary over a well-specified baud

period, determined by the transmitter's modulation rate. The spectrum of such a

20   statistically independent modulated data symbol flow can be seen as repetitive with a

frequency identical to the baud rate used for the modulation.

The periodicity of the spectrum is evidenced by the intrinsic cyclostationary property of such baud-modulated signals. The repetition of the spectrum at multiple of the baud rate means that adjacent frequency bands will be correlated even after filtering is used at the transmitter. In some cases, filtering may preserve the energy of the secondary

5   frequency bands, leaving a strong correlation. In other cases, filtering will only leave a small fraction of the energy from the secondary frequency bands in an effort to band-limit the transmitted signals, therefore leaving a small "excess bandwidth" from which correlation still can be seen but with a lesser amplitude.

        In a system operating in an Annex C environment, NEXT cross-talk from existing

10   TCM-ISDN is the major performance-limiting impairment for the ADSL DMT transmission. From the property of cyclostationarity of the TCM-ISDN interferer to the ADSL-DMT signal, it is a major factor contributing to crosstalk interference in Annex C environment. In an Annex B system, the ADSL DMT signal is transmitted on the same twisted pair as an already existing ISDN link. As a result, the two signals are partially

15   overlapping channels.

        In both cases mentioned above, the property of cyclostationarity is present in the ISDN interference. Exploitation of this signal property can be used to allow the separation of the two temporally and spectrally overlapping communications signals. This can result in an enhanced waveform extraction and digital data detection of the

20   useful ADSL DMT signal.

Crosstalk, is an electrical energy radiating from bundles of wire converging at a

service provider's CO that produce an inconvenient disturbance known as Near-End

Crosstalk (NEXT) or Far-End Crosstalk (FEXT). Referring to the prior art of Figures 2a

and 2b, When TCM-ISDN downstream signals wander between channels of different

5   cables, line capacity takes a dive. "Near end" specifies that the interference derives from

an adjacent pair of cables at the same location. Usually, the twisted pairs are in the same

cable or bundle. Crosstalk is generally characterized as NEXT or FEXT. FEXT is

characterized by the disturbing pair's (in this case, the TCM-ISDN signal) source being

distant from the disturbed pair's (in this case the ADSL signal) receiver. In this case, the

10   disturbing signal propagates down the disturbing pair, crosstalk into the disturbed pair

and propagates the rest of the distance along the disturbed pair into the disturbed pair's

receiver.

Therefore, there is a need in the art of ADSL systems for a more efficient method

and system for reducing crosstalk, and to overcome the aforementioned interference

15   problems.

Summary of the Invention

An object of the present invention is to provide a method and apparatus for

reducing or eliminating near-end crosstalk (NEXT) and far-end crosstalk (FEXT)

20   interference on digital subscriber line (DSL) systems from integrated services digital

network (ISDN) systems that co-exist within the same binder or in adjacent binders, or

operate on the same twisted pair.

One embodiment of the present invention is directed to a method and apparatus

for a combined equalizer/cyclostationary crosstalk canceller that achieves equalization

5   and cyclostationnary crosstalk removal; the combined equalizer/cyclostationary crosstalk

canceller and method consists of frequency shifters represented by modulators at multiple

of the interferer baud rates, followed by adaptive filters, followed by decimators in some

situations, before a summation or recombination of the signals is performed The number

of shifters, length of the respective adaptive filters, the rate at which these filters operate

10   (which may differ from one filter to another) can vary, rendering the use of the

decimators optional.

Another embodiment of the present invention provides a first alternative structure

for conserving the higher sampling rates up until the recombination, followed by a

possible down-sampling. Keeping a high sampling rate may avoid aliasing effects, that

15   may have occurred if downsampling were performed before the recombination of the

signals.

Another embodiment of the invention is a method and apparatus operating with or

without decimators, but which incorporate filters in some of the respective frequency

shifted paths, such filters may be fixed in that their implementation is to isolate the

20   desired signal components of the interferer only, and such filters may be selected from a

group of filters consisting of low-pass, high-pass or band pass, and fixed one given that

the interferer is known. Alternative structures arises from multiple embodiments that may result from having the fixed filters placed upstream of the adaptive filters in the frequency-shifted paths, one or more fixed filters placed upstream of the demodulators, all paths including the main path having fixed filters placed upstream of the adaptive

5   filters. Yet another embodiment of the present invention is a method and apparatus of having the fixed filters placed downstream from the adaptive filters.

Other aspects and advantages of the invention will become apparent from the following detailed description, taken in conjunction with the accompanying drawings, illustrating by way of example the principles of the invention.

10

Brief Description of the Drawings

The present invention can be understood more completely by reading the following Detailed Description of the Preferred Embodiments, in conjunction with the accompanying drawings, in which:

15   Figure 1 is a graphical representation illustrating a conventional one-sided spectrum density of an ISDN interferer having a baud rate of 80 KHz.

Figure 2(a) is a graphical representation illustrating a TCM-ISDN downstream signal creating a NEXT on an upstream ADSL-DMT signal and a FEXT on a downstream ADSL-DMT signal.

Figure 2(b) is a graphical representation illustrating a TCM-ISDN upstream signal creating a NEXT on a downstream ADSL-DMT signal and a FEXT on an upstream ADSL-DMT signal.

Figure 3 is a simplified block diagram illustrating one embodiment of a

5 cyclostationary equalizer structure and noise canceller for a Multicarrier system such as DMT.

Figure 4 is a simplified block diagram illustrating an alternative embodiment of a cyclostationary equalizer structure and noise canceller optimized to avoid aliasing.

Figure 5 is a simplified block diagram illustrating an alternative cyclostationary

10 equalizer structure and noise canceller having fixed filters placed upstream from adaptive filters in accordance with an embodiment of the present invention.

Figure 6 is a simplified block diagram illustrating an alternative cyclostationary equalizer structure and noise canceller having fixed filters placed downstream from adaptive filters in accordance with an embodiment of the present invention.

15 Figure 7 is a simplified block diagram illustrating an alternative cyclostationary equalizer structure and noise canceller having one fixed filter placed upstream from demodulators in accordance with an embodiment of the present invention.

Figure 8 is a simplified block diagram illustrating an alternative cyclostationary equalizer structure and noise canceller having multiple fixed filters placed upstream from

20 demodulators in accordance with an embodiment of the present invention.

Figure 9 is a simplified block diagram illustrating an alternative cyclostationary equalizer structure and noise canceller having fixed filters placed upstream from adaptive filters including a main path in accordance with an embodiment of the present invention.

Figure 10 is a simplified block diagram illustrating a structure of a time domain

5   training of a cyclostationary TEQ, further illustrating a physical equalizer W and a target impulse response B.

Figure 11 is a graphical representation showing a typical bandwidth utilization of an ADSL DMT modem operating according to Annex B, without any ISDN noise canceller according to an embodiment of the present invention.

10   Figure 12 is a graphical representation showing a potential bandwidth utilization of an ADSL-DMT modem operating according to Annex B, with any ISDN noise canceller.

Figure 13 is a graphical representation showing a received ADSL-DMT downstream spectrum at channel output, with ISDN noise signal.

15   Figure 14 is a graphical representation showing a frequency shift operation on the received DMT plus the ISDN signal.

Figure 15 is a graphical representation showing a filtering operation of one of the TEQ branches.

Figure 16 is a graphical representation showing a result of combining the

20   individual TEQ branches before presenting the output to the detector.

Figure 17(a) is a graphical representation showing the W_0 equalizer match filtering the ADSL-DMT signal and rejecting the ISDN signal.

Figure 17(b) is a graphical representation showing a shifted spectrum of 80 KHz of the ADSL-DMT signal and the ISDN signal filtered by the W_1 equalizer.

5   Figure 17(c) is a graphical representation showing a shifted spectrum of 160 KHz of the ADSL-DMT signal and the ISDN signal filtered by the W_2 equalizer.

Figure 17(d) is a graphical representation showing a first two ISDN in-band lobes being suppressed to a level below other noise levels.

Figure 18 is a simplified block diagram illustrating one embodiment of an

10   equalizer structure for equalizing the channel and a separate cyclostationary noise canceller for a Multicarrier system such as DMT.

Figure 19 is a simplified block diagram illustrating an equalizer structure and a separate cyclostationary noise canceller with a one-tap filter in the main path in accordance with an embodiment of the present invention.

15   Figure 20 is a simplified block diagram illustrating another embodiment of a cyclostationary noise canceller training structure.

Figure 21 is a simplified block diagram illustrating a cyclostationary stand-alone noise canceller structure for a Multicarrier system such as DMT in accordance with one embodiment of the present invention.

12

Figure 22 is a simplified block diagram illustrating another embodiment of a cyclostationary canceller and equalizer training structure of the present invention.

Figure 23 is a simplified block diagram illustrating another embodiment of a cyclostationary canceller and equalizer training structure of the present invention.

5 Figure 24 is a simplified block diagram illustrating a combined cyclostationary canceller and equalizer training structure adapted for the training of the whole structure in accordance with one embodiment of the present invention.

Figure 25 is a simplified block diagram illustrating another embodiment of a combined cyclostationary canceller and equalizer training structure optimized for the

10 training of the whole structure.

Figure 26 is a simplified block diagram illustrating a mathematical representation of a frequency shifter structure showing a complex operation.

Figure 27 is a simplified block diagram illustrating a mathematical representation of a frequency shifter structure showing a complex operation where only the real part is

15 utilized.

Figure 28 is a simplified block diagram illustrating a mathematical representation of a frequency shifter structure showing a complex operation where both the real and imaginary parts are utilized.

Figure 29 is a simplified block diagram illustrating a reduced mathematical representation of a frequency shifter structure operation where only a single multiplication with a sine wave is performed.

Figure 30 is a simplified block diagram illustrating a cyclostationary equalizer structure and noise canceller having simple demodulation using a cosine or a sine in accordance with one embodiment of the present invention.

Detailed Description of the Preferred Embodiments

The following description is intended to convey a thorough understanding of the invention by providing a number of specific embodiments and details involving the reduction or cancellation of crosstalk in ADSL systems co-located with ISDN . It should be understood, however, that the invention is not limited to these specific embodiments and details, which are provided for exemplary purposes only. It should be further understood that one possessing ordinary skill in the art, in light of known systems and methods, would appreciate the use of the invention for its intended purposes and benefits in any number of alternative embodiments, depending upon specific design and other needs. For example, the system and method described below may also have application in reducing or canceling crosstalk in ADSL systems co-located with other types of cyclostationary disturbers.

One embodiment of the present invention is directed to a method and apparatus

that significantly reduces the NEXT and FEXT interferences due to the presence of ISDN

signals in the same bundle of twisted pair wires as an ADSL-DMT signal as

recommended ITU-T G.992.1 Annex B and Annex C. In reference to Figure 3, there is

5   shown a simplified block diagram **300** illustrating a method and apparatus comprising the

steps of receiving a signal **304,** that consists of the desired ADSL-DMT signal as well as

the interfering ISDN signal from a channel. Next, the received signal is demodulated

with demodulators **312, 314** and frequency-shifted by the baud rate of the interfering

ISDN signal by frequency shifters **316** and **318**. The original signal is passed onto a time

10   domain equalizer **306,** and the replicas of the received signal are passed to parallel time-

domain equalizers **308** and **310** to remove the interference and preserve the desired

signal. Next, the output of the parallel time-domain equalizers are individually

downsampled at downsamplers **320, 322** and **324** in order to reduce the sampling rate.

The downsampled signals are then added together at combiner **326**, where the frequency

15   shifted side lobes of the ISDN interferer signal cancels each other in the parts of the

spectrum shared with the ADSL DMT signal. The desired signal **328** is then passed onto

other parts of the receiver, such as FFT and slicer for further processing.

Referring now to Figure 4, there is shown a second embodiment of the present

invention. In particular, the illustrated first alternative structure **300,** conserves the higher

20   sampling rates up until the recombination. Keeping a high sampling rate may avoid

aliasing effects, that may have occurred if downsampling were performed before the

recombination of the signals. In the present embodiment, a block diagram **400** is shown with one downsampler **422**, used after the recombination at **420**, in order to reduce the sampling rate before the signal is passed onto the detector for further processing.

Referring now to Figure 5, there is shown a third embodiment of the present

5   invention **500**, wherein downsamplers are not incorporated in the receiver structure. However, a plurality of filters **514, 516** are incorporated in the respective frequency shifted paths. Such filters **514, 516** may be fixed in that their implementation is to isolate the desired signal components off from the interferer. In a preferred embodiment, the filters **514, 516** are selected from a group of filters consisting of low-pass, high-pass or

10   band pass, and a fixed filter in the event that the interferer is known. The alternative embodiment disclosed teaches a method and apparatus of having the fixed filters **514, 516** placed upstream from the adaptive filters **520, 522**, in order to isolate the desired signal components **526** from the interferer.

Referring now to Figure 6, there is shown a fourth embodiment **600** of the present

15   invention. In particular, the embodiment of Figure 6 is similar to that shown in Figure 5 in that downsamplers are not provided, but which incorporate filters **620, 622** in some of the respective frequency shifted paths. In the present embodiment, the fixed filters **620, 622** are placed downstream from the adaptive filters **616, 618** as shown in Figure 6.

Another embodiment of the invention is a method and apparatus **700**, operating

20   without downsamplers, but which incorporate the use of filters in the respective frequency shifted paths, such filters may be fixed in that their implementation is to isolate

the desired signal components of the interferer only, such filters are selected from a group of filters consisting of low-pass, high-pass or band pass, and fixed one (given that the interferer is known). The alternative embodiment disclosed teaches a method and apparatus of having one fixed filter **706**, operating in one of the frequency-shifted paths

5 and placed upstream from the demodulator **708**, in order to isolate the desired signal components from the overall signal and reject the interferer and by using only one filter and not utilizing any downsamplers, the receiver components are minimized, thereby reducing the size of the receiver as shown in Figure 7.

Another embodiment of the invention and in reference to Figure 8, there is shown

10 a method and apparatus **800**, operating without downsamplers, but which incorporate filters in some of the respective frequency shifted paths, such filters may be fixed in that their implementation is to isolate the desired signal components of the interferer only, such filters are selected from a group of filters consisting of low-pass, high-pass or band pass, and fixed one (given that the interferer is known). The alternative embodiment is

15 similar to the embodiment of Figure 7, except disclosed method and apparatus teaches a method and apparatus of having more than one fixed filters **806**, **808** operating in one of the frequency-shifted paths and placed upstream from respective demodulators **810**, **812** in order to isolate the desired signal components from the overall signal and reject the interferer of having fixed filters placed upstream from the demodulators in the

20 frequency-shifted path to isolate the desired signal components of the interferer, as shown in Figure 8.

Another embodiment of the invention and in reference to Figure 9, filters **917**,

916, and **918** are placed in the path of the main received signal as well as the respective

frequency shifted paths, such filters may be fixed in that their implementation is to isolate

the desired signal components of the interferer only, such filters are selected from a group

5   of filters consisting of low-pass, high-pass or band pass, and fixed one when the

interfering signal is known. The alternative embodiment, disclosed in Figure 9, teaches a

method and apparatus of implementing a fixed filter **914** placed in the main path of the

received signal, in order to filter out any out-of-band interference to the ADSL-DMT

signal, as well as placing filters **916** and **918** downstream from the demodulators in the

10   frequency-shifted path to isolate the desired signal components of the interferer.

Yet, in another embodiment of the present invention and in reference to Figure

10, a method and apparatus of training the crosstalk canceller and equalizer of the present

invention is disclosed herein. In Figure 10, the desired signal and denoted by **1002**, is

transmitted through an unknown channel **1004**, that distorts the desired signal, the

15   distorted signal is combined with background noise **1006**, by combiner **1008**, producing a

received signal **1010**, and filtered by adaptive filters **1020**, **1022** and **1024**. Then the

output of the filters is transmitted to respective downsamplers **1026**, **1028** and **1030** to

produce filtered outputs. In order to filter the received signal **1010**, so that it resembles

the desired signal **1002**, an adaptive algorithm is employed. To achieve that, a replica of

20   the desired signal **1032**, is locally generated at the receiver, and transmitted to a number

of target filters **1044**, **1046** and **1048**. Error figures **1056**, **1058** and **1060** are computed

from the difference of the outputs of equalizers **1020**, **1022**, **1024** and impulse response

target filters **1044**, **1046** and **1048**. The computed errors are then used to derive and

compute both sets of equalizer coefficients (W_0, W_1,...W_{M-1}) and target impulse response

coefficients (B_0, B_1,....B_{M-1}); these error figures bare then used jointly or separately to

5   derive the adaptive coefficients close to their optimum values with conventional adaptive

algorithms such LMS, RLS, or constant modulus algorithm (CMA).

Yet, in another embodiment of the invention and in reference to Figure 18, a

method and apparatus **1800** of a crosstalk canceller is disclosed, in which an independent

structure is located at the front of the receive section of a transceiver, where the

10   equalization of the channel is not ensured by the crosstalk canceller **1814**, **1816** and **1818**,

but rather by a subsequent Time Domain Equalizer (TEQ) structure **1824**. It is a

separated channel, one for equalization and another for interference rejection apparatus

and method. The equalizer's operation shown Figure 18 is independent of the crosstalk

remover. The role of the crosstalk canceller is to "clean up" the useful signal from in-

15   band crosstalk before further processing. The training and optimization of the crosstalk

canceller part can be done with or without the presence of the useful signal (in this case

the DMT signal).

By choosing the embodiment of training the crosstalk canceller in the absence of

the useful signal, and only in the presence of the cyclostationary interference, the output

20   signal **1822** in Figure 18 is minimized, and as expected the crosstalk canceller operates in

such a manner that it will cancel the interference by itself, across the whole spectrum

represented in Figure 1, as desired. The spectral components present in each of the side-lobes of the interference signal may be used to completely cancel the other spectral components of the other side-lobes of the interferer. However, since the structure is trained in the absence of the useful signal, the filters **1814**, **1816** and **1818** constituting

5   the crosstalk canceller may yield an undesirable effect on the useful signal, which will also propagate through the crosstalk canceller structure. Such undesirable effects may be (a) distortion in the direct path through filter **1814**, in Figure 18, and (b) folding the useful signal upon itself, creating a self-interference through the secondary frequency shifted paths and recombination at the canceller output. In order to overcome the

10   problem of distortion in the direct path through filter **1814** in Figure 18, and in accordance with one embodiment of the invention and in reference to Figure 19, is that a simple delay **1914** is implemented in place of the filter **1814** in Figure 18 in the direct path during training. Such an embodiment of the current invention prevents the primary path of the useful signal from being distorted. It can easily be obtained by constraining

15   the filter **1814** in Figure 18 to a single tap filter during training and steady-state operation. And in order to avoid folding of the useful signal upon itself which creates self-interference through the secondary frequency shifted paths one exemplary embodiment of the present invention is to incorporate a training sequence that operates in the presence of both the useful signal and the interferer, such a method is illustrated in Figure 20, where

20   the useful signal **2002** is transmitted through the channel, the channel represented by a simple delay **2004** for ease of understanding, at the same time, a replica of the useful

signal **2002**, represented by **2028** in Figure 20 which is noiseless is applied with a delay

2030. At the output of the channel, a cyclostationnary interference is added. During

training the replica of the known training sequence **2028** is locally generated at the

receiver (knowing the same sequence **2002** is being transmitted during a given moment

5   of the start-up sequence), and then is used to perform the training of the crosstalk

canceller. The optimization may not take place by minimizing the output of the crosstalk

canceller itself, rather the optimization is achieved by minimizing the difference between

the output of the canceller **2026** and a replica of the input noiseless sequence **2028**

applied with a delay **2030**. The object of the embodiment is to have at the output of the

10   crosstalk canceller a signal, which is close to or identical to the noiseless form **2002**.

Thus, the crosstalk canceller removes the cyclostationnary interference without affecting

the useful signal. The error denoted by e_0 may be used to adapt the crosstalk canceller

during the training sequence.

It should be noted that in Figure 21, the presence of the TEQ is not necessary, the

15   channel being a pure delay does not introduce distortion to the useful signal. Hence, the

TEQ need not undo any distortion.

In the more realistic case where a real channel **2204** creates attenuation and

distortion to the useful signal, a TEQ **2230** will be necessary, and can possibly be placed

downstream from the crosstalk cancellers **2220, 2222,** and **2224**. In reference to Figure

20   22, an embodiment of the current invention is to place an additional filter **2236** for the

training phase. Its presence is necessary since the useful signal **2202** to which it is

desired to have the crosstalk's output resemble as closely as possible, suffers attenuation and distortion through the unknown channel **2204**. After proper convergence, it is expected that the filter **2236** would become a replica of the unknown channel **2204**. Alternatively, the filter **2236** could also be devised independently through proper channel

5   estimation, before the training of the crosstalk cancellers **2220**, **2222**, and **2224**. However, it is suggested in the embodiment that both convergence of the filter **2236** and the crosstalk cancellers **2220**, **2222**, and **2224** can be achieved jointly in an adaptive manner. The objective of the training of the crosstalk cancellers **2220**, **2222**, and **2224** remains identical as in the manner outlined earlier, to ensure that its output resembles as

10   closely as possible the known noiseless sequence **2232** applied to filter **2236**, which is expected to approach a replica of **2204**. In order for the crosstalk canceller's **2220**, **2222**, and **2224** output to be similar to a noiseless output of the channel **2204**, the cancellers **2220**, **2222**, and **2224** has to remove most of the interferer disturbance. Once that is achieved, the output of the crosstalk canceller **2228** can then be fed to the TEQ **2230** for

15   channel equalization.

In another embodiment, and in reference to Figure 23, the time domain equalizer, TEQ **2330** is trained after a successful training of the crosstalk cancellers **2320**, **2322**, and **2324** in the same manner depicted in Figure 22 with which a classical TEQ would be trained in DMT. The TEQ is trained, such that its output matches as closely as possible

20   the output of a so-called target filter **2336** of a specified length (Cyclic prefix length) fed with a replica of the noiseless known training sequence **2332**. The crosstalk cancellers

22

2320, 2322, and 2324 frozen with their optimum coefficients during the TEQ training, removing all cyclostationary disturber, without affecting the useful signal. The TEQ training therefore takes place as if there were no disturber. As in the absence of an interferer, the optimization of the TEQ is done such that the combined channel C(n) /

5   TEQ impulse response does not exceed the target impulse response of target filter 2336, corresponding to the cyclic prefix length of a DMT system. By implementing this embodiment, it is ensured that no inter-symbol interference (ISI) between consecutive DMT symbols takes place, and that the orthogonality between carriers is maintained within a same DMT symbol, avoiding Inter-Channel Interference (ICI). In figure 23, the

10   crosstalk canceller propagates the receive signal (useful and interference) in it's direct path. Also it's secondary paths perform a frequency-shift of the interferer and subtract it from the main path output, while minimizing the amount of self-interference to the useful signal, hence, at its output, the signal 2328 is free of interference. The TEQ 2330 then equalizes the noiseless, useful signal to the cyclic prefix length. It is an independent

15   equalizer and crosstalk canceller structure. However, the crosstalk canceller has been trained in the presence of the useful signal, in order not to degrade it.

In another embodiment of the current invention and in reference to Figure 24, a target filter 2434 is introduced into the structure and the TEQ filter is incorporated in the direct path of the crosstalk canceller as filter 2420, so that the training of the crosstalk

20   canceller is done jointly with the one of the TEQ. The filter coefficients are derived such that the combination of the output of the TEQ filter with the output of the crosstalk

canceller matches as close as possible in a minimum mean square error sense, the output of the target filter **2434** of a cyclic prefix length fed by a replica of the noiseless transmitted sequence **2430**. When convergence is achieved, two objectives of the filter structure maybe achieved, equalizing the useful signal to the cyclic prefix length and

5   rejecting the cylostationnary interference. In this structure, however, the respective roles of the crosstalk canceller and the TEQ will be less clearly identifiable. Equalizing the useful signal will primarily be performed by the **2420**, but since the filter **2420** will affect the interference signal as well through this process, it is expected that the filters **2422**, and **2424** of the other branches will have to compensate for this effect in order to properly

10   cancel the interferer itself. Therefore, the filters **2420, 2422,** and **2426** of the structure have been given a same labeling W_0, W_1....W_{M-1} since their optimum setting is a joint optimization process.

When the series of corresponding target filters **2422**, and **2426** with frequency shifts are implemented for proper optimization, the filters tend to filter not only the side-

15   lobes of the interference signal in order to cancel it in the main branch, as they would have in a separate crosstalk TEQ structure, but to some extent, some energy of the useful signal is let through in the same manner. However, when some energy of the useful signal is let through the secondary paths, it is needed to ensure that the corresponding target impulse response of the combined channel and secondary paths be shorter than the

20   cyclic prefix length, otherwise, the undesirable effect will be to create ISI and ICI through the secondary frequency shifted branches, similar to the one that would be

created if the B_0 target impulse response length were exceeded in the main path. In another implementation of the embodiment of Figure 24, and in reference to Figure 25, a series of target impulse responses filters **2542**, **2544**, and **2546** with frequency shifts, which will be used to constrain the respective combined channel **2504** and the filters

5   **2520**, **2522** and **2524** below the cyclic prefix length is included in the structure. By implementing such filters, undesirable ISI and ICI effects are limited, when the useful signal energy propagates through the secondary paths. The error signals $e_0, e_1,.. e_{M-1}$ can be used individually or in any combination to adapt the various filters **2520**, **2522** and **2524** and target filters **2542**, **2544**, and **2546**.

10   While the invention has been described in conjunction with the preferred embodiments, it should be understood that modifications will become apparent to those of ordinary skill in the art and that such modifications are intended to be included within the scope of the invention and the following claims.